2011

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EVALUATION OF A SEPARATION ASSISTANCE DISPLAY IN A MULTI-ACTOR EXPERIMENT

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In the past, several display concepts have been developed, as aids in the task of airborne self-separation. In several of these display concepts, the interface helps the pilot solve the conflict, as opposed to automation providing an explicit resolution. Especially in this case of manual problem solving, (implicit) interaction between the actors in a conflict becomes an important factor. An experiment was conducted to evaluate an EID-inspired, constraint-based separation assistance display, where all aircraft in each conflict were controlled by pilot subjects. In the experiment, several conflict scenario's have been evaluated, where coordination between pilots could either follow implicitely from the conflict geometry presented by the interface, or, require additional, explicit rules ("rules of the air") to be solved in a coordinated fashion.

In the current ATM concepts for unmanaged airspace, aircraft will fly completely predetermined 4D trajectories, where automation will provide resolution advisories for traffic (or other) conflicts that may result from uncertainties that arise during flight (RTCA, 2002; SESAR Consortium, 2007). In this situation, the pilot's task will be one of monitoring separation, and selecting and applying resolution advisories, provided by the automation. He should, however, be able to judge the fidelity of a proposed resolution, and be able to intervene in case the automation fails.

Furthermore, because conflicts will be resolved in a decentralized fashion, determining the resolution to a conflict will require coordination between the actors in that conflict. This means that for automated, as well as manual conflict resolution, predictability of decisions will be essential to guarantee an acceptable level of safety. In situations where there is not enough time for negotiation, implicit coordination will be required, e.g., by following a predetermined set of rules that dictate which aircraft should maneuver, and how it should maneuver. In worst-case scenarios, pilots will have to manually determine resolution maneuvers, for instance when the automation has failed, or other reasons why a pilot decides to resolve the conflict manually. This poses limits on the complexity of the coordination rules. For automated resolution advisories, high rule complexity can make it difficult for pilots to understand the rationale behind resolution advisories, potentially resulting in non-conformance and distrust of the system (Schild & Kuchar, 2000; Lee & Moray, 1992; Parasuraman & Riley, 1997).

For adequate situation awareness, and proper interaction with automated systems, and between actors in a conflict, it is therefore necessary for regulation and automation to be transparent and understandable to the operator. The work presented in this paper is part of an ongoing study on the design of a separation assistance interface that can fulfil this role (van Dam, Mulder, & van Paassen, 2008; Heylen, van Dam, Mulder, & van Paassen, 2008; Ellerbroek, Visser, van Dam, Mulder, & van Paassen, 2011). The display concepts developed in this study try to realize proper support, by showing the implications of other traffic for the affordances of locomotion, and how they relate to constraints that result from ownship performance limits. By going beyond visualizations that relate only to the automation logic, these displays help pilots gain deeper knowledge of the functions and relations within the work domain. These displays should provide support in routine as well as unforeseen situations, where the pilot may have to rely on his own skills to resolve a conflict.

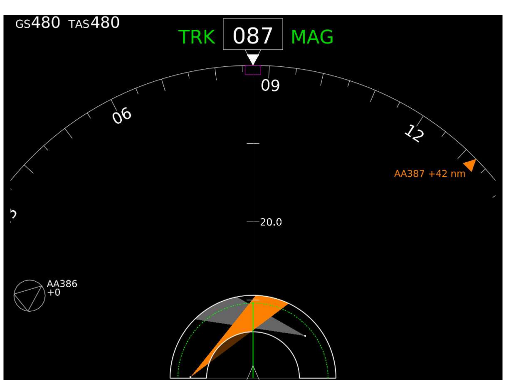

Figure 1: The horizontal separation assistance display is based on a classical Boeing navigation display, with an added separation assistance overlay. The overlay provides a functional presentation of the affordances for aircraft airspeed and track angle using a horizontal projection of the three-dimensional velocity-vector affordance space.

The work presented in this paper will focus on the coordination rules that can be used with these display concepts, in multi-actor resolution of traffic conflicts. An experiment was defined to evaluate coordination behavior in worst-case scenarios, in which pilots have to resort to manual determination of conflict resolutions. In the experiment, a horizontal, constraint-based separation assistance display was available to the pilots to evaluate conflicts, and to determine resolution maneuvers, see Figure 1. The following two sections will present a set of coordination rules that can be used with the display, and describe the experiment and discuss the results, respectively. The paper concludes with a summary of these findings, and plans for future work.

Implicit coordination for manual control

For implicit coordination between actors in a conflict to function consistently well, a set of rules must be defined that keeps pilots from selecting opposing resolutions. These rules may be based on extensions of the visual flight rules (International Civil Aviation Organization, 1996), but in most cases, a cooperative resolution can also be derived from the conflict geometry, see Figure 2. This type of coordination is related to the conflict solution that results in *minimum path deviation*. Consider the nominal aircraft position at time t:

$$\mathbf{x}(t) = \mathbf{x}_0 + \int_{t_0}^{t} \mathbf{V}_{orig}(t)\,\mathrm{d}t \tag{1}$$

The path deviation for a maneuver can be derived from difference between maneuver and original velocities:

$$\Delta x = \int_{t_0}^{t_1} \left|\mathbf{V}_{sol}(t) - \mathbf{V}_{orig}(t)\right| \mathrm{d}t = \int_{t_0}^{t_1} \left|\Delta\mathbf{V}_{sol}(t)\right| \mathrm{d}t \tag{2}$$

Using (2), it can be shown that the path deviation is minimized by minimizing $\Delta\mathbf{V}_{sol}$.

Figure 2 shows a traffic conflict with two aircraft, and the derivation of their velocities relative to each other. The circles visualize the horizontal separation margin around each aircraft, and the areas between the triangle lines tangent to each circle show the conflicting values for each relative velocity vector. In this figure, $\Delta\mathbf{V}_{sol}$ is the vector distance between $\mathbf{V}_{rel}$ and the nearest constraint zone leg. The shortest distance is found when $\Delta\mathbf{V}_{sol}$ is taken perpendicular to the constraint zone leg (van Dam et al., 2008; Bilimoria, 2000). Figure 2 also illustrates that, as long as $\mathbf{V}_{rel}$ is closer to one leg than to the other, a single optimum for $\Delta\mathbf{V}_{sol}$ can be found, and that both aircraft share this optimum. Therefore, implicit coordination is guaranteed when the optimum is selected as a resolution.

For situations where there is no unique geometrically optimal solution, an additional set of rules is required. For the experiment, the following 'rules of the air' were used: aircraft being overtaken have the right of way and overtaking aircraft must remain clear by altering heading to the right. When two aircraft are approaching each other head on they must both alter heading to the right.

Because the separation assistance display presents the pilot with a velocity action space that is based on the conflict geometry, it can support both coordination strategies. Geometrically optimal solutions can be selected using the display, by changing speed and heading to move the speed vector to the nearest conflict zone leg. Also, selecting a velocity vector to the left, or to the right of a conflict area is analogous to passing the intruder aircraft to the left or the right. Ownship will pass in front of the intruder when the velocity vector crosses the respective constraint area on the display.

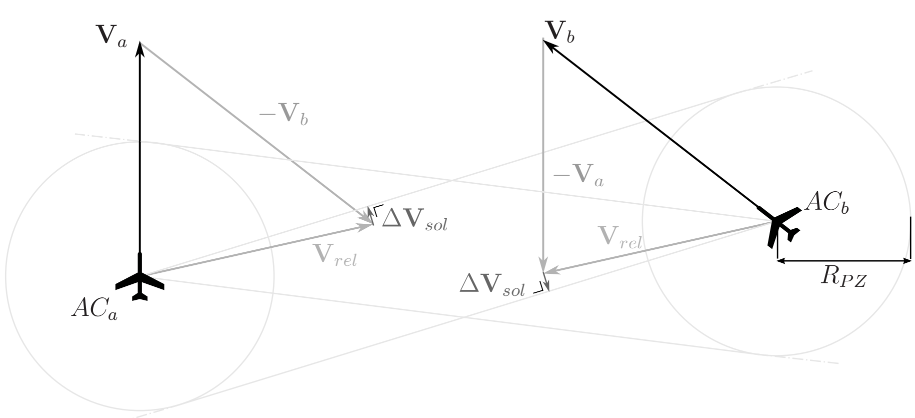

Figure 2: Geometrically optimal solutions guarantee implicit coordination, for all conflict geometries with the exception of collision courses. Because of the rotational symmetry of constraint zones of both aircraft, selecting the optimal solution for aircraft AC_a will always be complementary to the geometrically optimal solution for aircraft AC_b.

Experiment

To evaluate the coordination of manual resolution maneuvers between actors in traffic conflicts in unmanaged airspace, a multi-actor, traffic separation experiment was performed. To obtain analyzable pilot responses, as well as the interactions between those responses, pairs of pilots were placed in two-aircraft traffic conflict situations, with a loss of separation in the near to short term future.

Method

Each session consisted of a continuous presentation of five consecutive conflict scenarios, that needed to be resolved manually, with the aid of a constraint-based separation assistance display. Traffic conflicts were always between two human actors, and were designed using parameters *conflict angle, time to first loss of separation*, and *CPA distance*.

Apparatus and Aircraft Model: The experiment was performed on two physically separated, fixed-base pilot stations. Each setup featured two LCD screens: one showing a Primary Flight Display, the other showing a Navigation Display with separation assistance overlays. Participants could control display settings and auto-pilot heading and speed modes through physical EFIS selector and Mode Control panels.

The aircraft models employed in the simulation were low-order, quasi-linear models of a Boeing 707-300, and an Airbus A330, see table Table 1. The model coefficients were obtained from EUROCONTROL's BADA aircraft database. The simulation was run in realtime, at an update rate of 100 Hz. The experiment was conducted with zero wind, and no turbulence.

Experiment Design and Procedure: The experiment was designed as a within-subjects repeated-measures, where factors *aircraft model* and *conflict geometry* were varied. The *aircraft model* factor was introduced to illustrate the effect of a reduced speed margin on the availability of (optimal) resolution options. Because every aircraft type suffers from reduced speed margins at increasing altitude (stall speed and critical mach number converge with increasing altitude), speed margins are an important factor for conflict resolutions at cruise altitude.

The conflict geometry was designed based on three factors: conflict angle, time to first loss of separation, and the distance between the two aircraft at the closest point of approach. Here, the conflict angle determines the shape and orientation of the constraint zone, and the magnitude of the closing speed between the two aircraft. Varying conflict angle between scenarios, therefore, is a way to minimize memorizing/learning effects between scenarios. The distance at the CPA, d_{CPA}, determines whether a unique optimal solution to the conflict can be found ($d_{CPA} \neq 0$), or whether coordination based on an additional set of rules is required ($d_{CPA} = 0$). The time to first loss of separation varied between 3 - 5 minutes, which meant a medium to high level of urgency for each conflict scenario. Each of the conflicts was designed with two participating aircraft.

Each experiment session required two subjects. These subjects were invited and briefed separately, and were not informed that the conflicting aircraft were controlled by a second participating pilot. After a briefing on the experiment and the functioning of the separation display, subjects performed approximately one hour of training. To avoid learning effects, but still reach a stable level of performance and sufficient understanding of the information presented by the separation assistance interface, separate example scenarios were used for training.

The measurement phase consisted of 10 conditions, presented in a randomized block design. Subjects performed each scenario in both aircraft, resulting in 20 measurement trials per subject. The trials were combined in blocks of five continuous conflict scenarios. This meant that for each set of five scenarios, all participating aircraft were present in the same simulated airspace, during the course of the five trials. Aircraft that do not participate in the current conflict were placed at different flight levels, to avoid previous and future conflicts having an effect on the affordance space of the current trial. After each trial, subjects were asked to fill in a short questionnaire concerning their resolution decision.

		Boeing 707-300	Airbus A330
TAS_{min}	[kts]	282.4	331.1
TAS_{max}	[kts]	530.1	471.5
TAS_{cruise}	[kts]	485.0	432.0

Table 1: *Relevant data for the aircraft models in the experiment. The difference in cruise speed influences conflict geometry, and the reduced speed margin for the Airbus can limit the resolution possibilities.*

Table 2: *Rules and strategies for conflict resolution.*

1.	Safety has the main priority: Ensure sufficient separation at all times.
2.	Avoid resolutions that result in parallel tracks.
3.	If available, apply the geometrically optimal solution.
4.	When a unique optimal solution is not available, apply rules of the air.
4a.	An aircraft being overtaken has the right of way and the overtaking aircraft must remain clear by altering heading to the right.
4b.	When two aircraft are approaching each other head on they must both alter heading to the right.
4c.	Aircraft from the right have the right of way. Remain clear by passing behind that aircraft.

Subjects and Instructions to Subjects: Sixteen experienced glass-cockpit pilots participated in sets of two, 15 male, and one female. Experience in terms of flight hours per pilot ranged from $2,000$ to $16,700$ hours. Subjects were asked to perform an experiment, where they should resolve traffic conflicts in unmanaged airspace. They were informed that the results would be used to evaluate a concept for a separation assistance interface. To avoid “gaming” effects, (e.g., pilots creating, or prolonging conflicts on purpose), pilots were not informed that there was a second participant, and that they were, in fact, flying against a human “opponent”. Instead, they were told that during the measurements, intruder aircraft could participate in the resolution of a conflict, by using certain automated logic.

Prior to the experiment, pilots received a short briefing on the geometrical concepts behind the display, how to use the display, and on the experimental setup. An important aspect of this briefing was to instruct the pilot on the rules and strategies for conflict resolution, see Table 2

Dependent Measures: Dependent measures for this experiment consisted of several objective and several subjective measures. Objective measures were the *solution choice per pilot* in terms of vector change dimensions (heading and/or speed), and applied tactic (optimal state change vs. rule of the air), and the level of cooperation between pilots. *Safety* was measured in terms of minimum separation, and the initial reaction time was used as a measure of *performance*. These measures were constructed from recorded parameters position, heading, and selected speed and heading. Subjective measures consisted of online SA questions, and a post-experiment questionnaire.

Experiment Hypotheses: Several studies involving manual (horizontal) conflict resolutions found that pilots prefer to keep velocity constant (Hoekstra, 2001; Steens, van Dam, van Paassen, & Mulder, 2008). It was therefore hypothesised that the majority of the maneuvers would be heading-only. It was also hypothesised that conflict geometries with a small, non-zero expected CPA distance result in the largest amount of opposing resolutions, as the choice between the optimal solution and applying rules of the air is less clear for such conflicts. Conflict geometries where $d_{CPA} = 0$ will show more coordination based on the rules of the air, whereas conflict geometries with large expected CPA distances will mostly be solved implicitely, where pilots use the shortest-way-out principle.

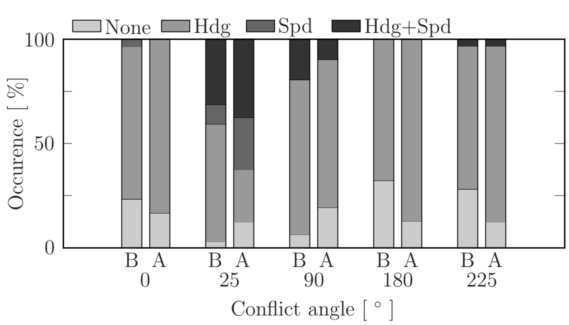

Figure 3: Maneuver dimensions sorted by conflict angle and aircraft type (*B = B707, A = A330*).

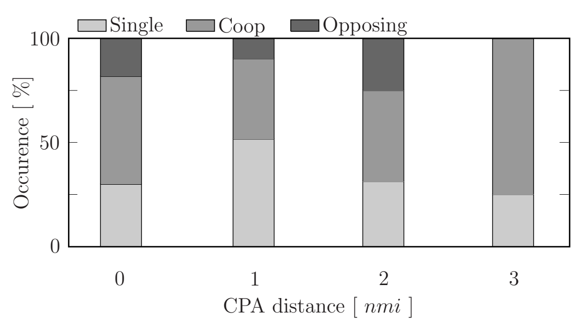

Figure 4: Level of cooperation between pilots sorted by conflict CPA distance.

Results

The resolution maneuvers in the experiment can be grouped by the flight parameters that were changed to resolve each conflict. For horizontal conflict resolution the available maneuver options are heading and speed changes. Therefore, solution choice is a categorical measure with four levels: *no action*, *heading only*, *speed only*, and *combined heading and speed*. The selection of a maneuver will depend on conflict geometry, aircraft performance limitations, phase of flight, and personal or airline preference. Table 3 shows the maneuver choice average for the entire experiment. As was hypothesised, the majority of the resolution maneuvers was heading only (almost 70 %), which can be attributed to personal or airline preference (Hoekstra, 2001). Figure 3 shows the maneuver choice sorted by conflict angle and aircraft type. For conflict angles $0°$, $180°$, and $225°$ this figure shows that (nearly) no speed maneuvers were used. These conflict angles result in (near) head-on or parallel (take-over) courses. In these situations, speed changes have no effect other than speeding or delaying a loss of separation, and only heading changes can be used to resolve such conflicts. A notable exception to the preference for heading resolutions is found in the $25°$ conflict angle scenarios, especially for the A330 (61% of the resolutions involved a speed change). In this situation, large heading changes are required to resolve the conflict. Also, for the A330, the max. speed line hides the tip of the intruder triangle, making it difficult to detect intruder intent, and impossible to determine the correct coordination rule. Giving way to the intruder by slowing down might then be considered the safest course of action.

Figure 4 and Table 4 show the level of cooperation between pilots, by CPA distance, and on average, respectively. Table 4 shows that pilots selected opposing solutions in 16% of the measured trials. This can be a matter of insufficient training, but it can also be an indication of a weakness of the interface. The most prominent cause for the opposing solutions was that the two pilots applied different rules: 64% for scenarios where $d_{CPA} = 0$, and 45% for scenarios where $d_{CPA} \neq 0$. These are errors where the wrong rule is applied. For all values of d_{CPA} this can be an indication that pilots could not reliably retrieve the required information from the display. In other cases, the correct rule was applied, but an error was made while evaluating the rule (7% for $d_{CPA} = 0$, and 55% for $d_{CPA} \neq 0$). In scenarios where $d_{CPA} = 0$, the direction of the maneuver depends on a previously stored 'rule of the air'. Therefore, when a wrong maneuver is made in such a scenario, it is because the pilot did not remember the applicable rule correctly. For scenarios where $d_{CPA} \neq 0$, the rule requires the direction of the maneuver to be derived from the display. In such scenarios, an erroneously applied rule can also be an indication that pilots could not retrieve the required information from the display.

50% of the measured trials were solved cooperatively. Figure 4 shows that this occured most frequently for scenarios with the largest conflict CPA distance. In situations where d_{CPA} is large, the velocity vector of ownship is close to the edge of the constraint zone belonging to the conflict. The optimal solution (the shortest way out of the triangle) is clearly visible on the interface, and guarantees implicit coordination when both parties strive for minimum path deviation. The scenarios with the smallest, non-zero CPA distance showed the lowest percentage of cooperation. In these situations, the optimal solution is less evident, and the choice between applying the optimal solution or applying the rules of the air becomes less clear.

The minimum separation was used as a measure of safety, by comparing the measured value to the defined separation minimum. The separation minimum was violated in 3 out of 160 measured trials. In all three cases, this occurred during a premature return to nominal heading and speed, and in all cases, the incursion was minimal. Reaction time was used as a measure of performance, but showed no significant variation across conditions.

As a subjective measure, pilots were quizzed randomly from a set of traffic awareness questions during the experiment. Although most questions were answered correctly, there are two notable exceptions. When asked whether the other aircraft was slower or faster than the own aircraft, pilots gave more unsure and wrong answers in conflict scenarios where the tip of the conflict zone (which also indicates the tip of the intruder velocity vector) was not visible on the display. Another question that was often answered wrongly was whether or not the other aircraft participated in the resolution maneuver. This cue is visible from the movement of the conflict zone on the display, which can be difficult for pilots to see without extra visual cues. Results from the post-experiment questionnaire also identify this as the most important issue with the display.

Table 3: *Percentages maneuver choice.*

None	16.67 %	Heading only	68.91 %
Speed only	3.85 %	Heading and speed	10.58 %

Table 4: *Percentages pilot cooperation.*

Single pilot solution	33.97 %
Cooperative solutions	50.00 %
Opposing solutions	16.03 %

Conclusions

A multi-actor, traffic separation experiment was performed, to evaluate the coordination of manual resolution maneuvers between actors in traffic conflicts in unmanaged airspace. Similar to previous studies, results from the experiment showed a considerable preference for heading-only maneuvers. As expected, difficulties with implicit coordination between actors in a conflict occurred for conflict geometries that do not clearly fall into a single category of coordination rules.

In the experiment, sixteen pilots participated, in pairs of two. For practical reasons, this is already a considerable amount of subjects. However, because of the nature of most of the measurements (i.e., categorical data with uneven expectations for the outcome per category), sufficient statistical power in the data requires a sample size closer to 50 groups, or 100 pilots, possibly even more. Because an experiment of this magnitude is difficult to realize, a follow-up study has been initialized that employs pilot decision models in a Monte-Carlo simulation, in an effort to identify the influence of behavioral characteristics on separation coordination and safety.

Acknowledgements

The authors gratefully acknowledge the pilots that participated in this study, and would like to thank MSc students W. M. G. Pas and R. W. Jutte for their help in carrying out the experiment. This work has been co-financed by the European Organisation for the Safety of Air Navigation (EUROCONTROL) under its research grant scheme of the innovative studies programme. Additional funding for this project is provided by the National Aerospace Laboratory (NLR), The Netherlands. The content of the work does not necessarily reflect the official position of EUROCONTROL nor NLR on the matter.

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